Perturbation for Resonant Microwave Cavities Electric Field perturbation using dielectric bead: Bead-pull

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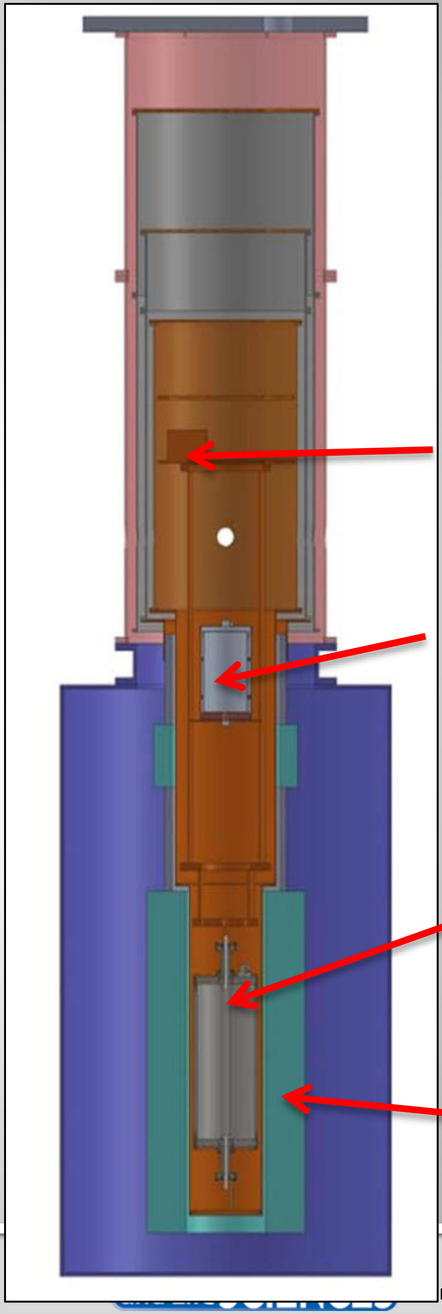
ADMX-HF: Operational Experiment

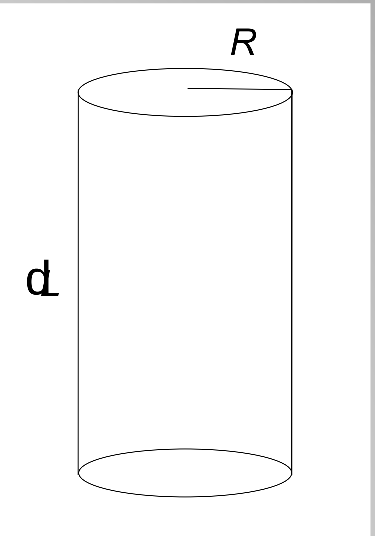
- Experiment achieves a base temperature of 25 mK.
- Magnet small volume high-field, superconducting solenoid(9 T 40 cm × 16.5 cm bore)
- Quantum Limited noise performance with use of JPA's.
- Cu plated S.S. and annealed.
- First cavity 3.6 - 5.8 GHz for TM_{010} mode.
- Q ~ 40,000 , of order predicted by the anomalous skin depth limit.
- Cavity : L = 10" and i.d = 4".
- Current status fully operational and first data has been taken.



Resonant Microwave Cavities

Application of Maxwell's equations for a cylindrical cavity geometry with appropriate boundary conditions.

$$\left(\nabla^2 + \mu\varepsilon\omega^2\right)\left\{E, B\right\} = 0$$



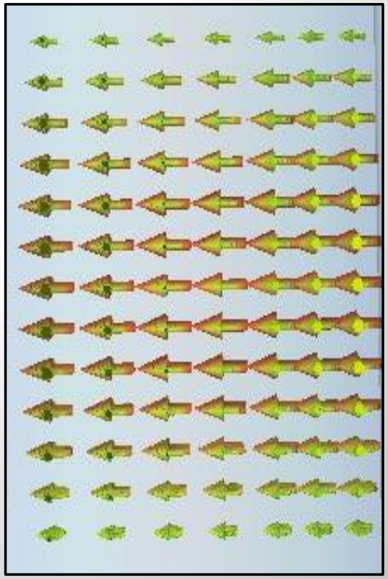
The frequency corresponds to a Transverse Magnetic and Electric field (TM,TE)

$$\omega_{mnp} = \frac{1}{(\mu\varepsilon)^{1/2}}\left(\frac{J_{mnp}^2}{R^2} + \frac{p^2\pi^2}{d^2}\right)^{1/2}$$

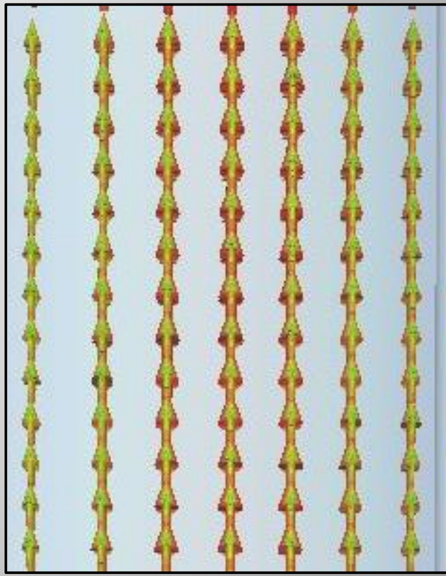
For the lowest order TM mode the frequency

$$\omega_{010} = \frac{2.405}{(\mu\varepsilon)^{1/2} R}$$

TE



TM



Electric Fields

Resonant Conversion of Axion in a Cavity

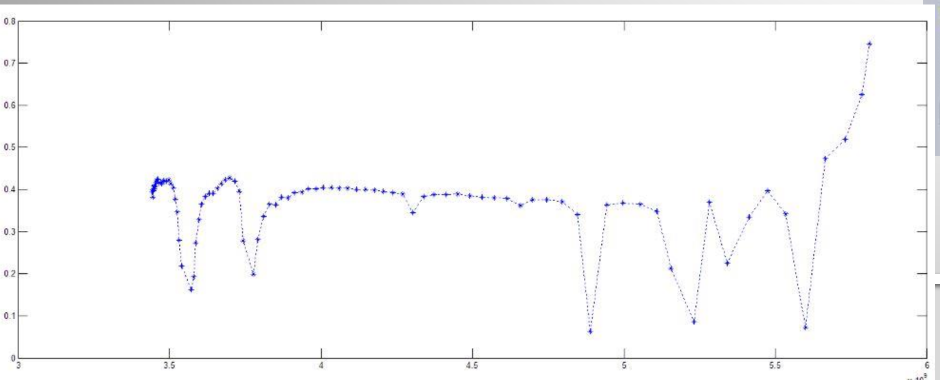
The Lagrangian relates coupling the Axion to the field arrangement.

$$\mathcal{L} = -\varepsilon_0 g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

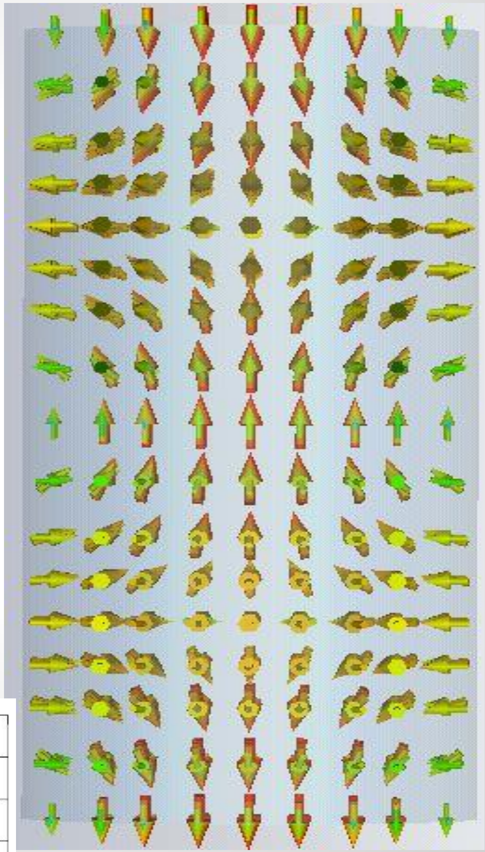
The form factor f_{nlm} the volume of the cavity that can interact with the Axion.

$$f_{nlm} \equiv \frac{\left(\int_V dV \mathbf{E} \cdot \hat{\mathbf{z}}\right)^2}{V \int_V dV \varepsilon_r E^2}$$

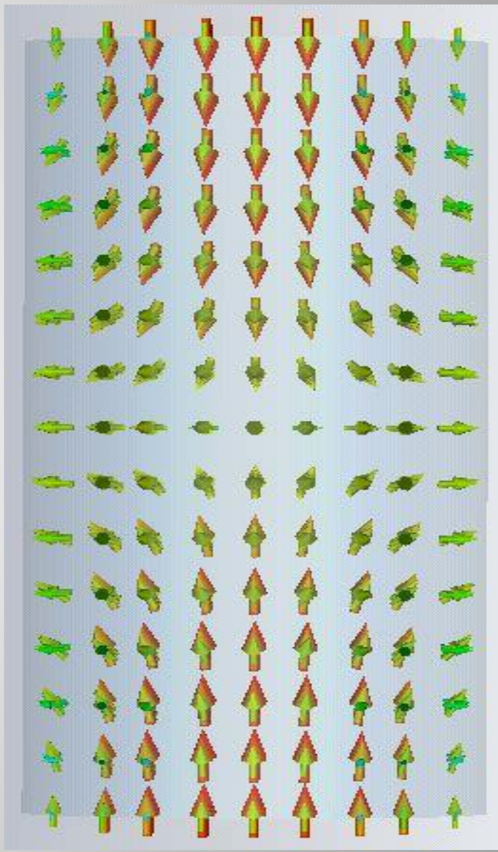
For the TM_{010} theoretical max $f_{nlm} \approx 69\%$ of total volume.



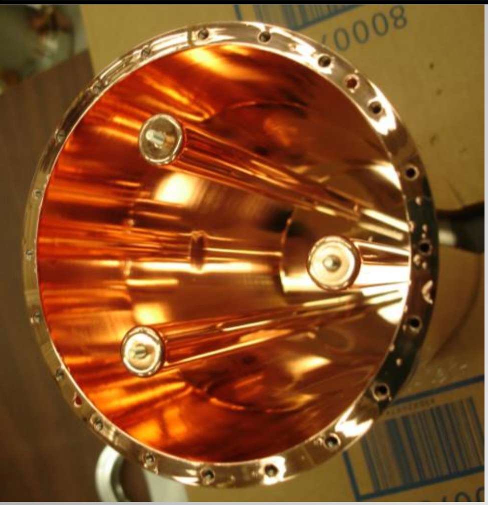
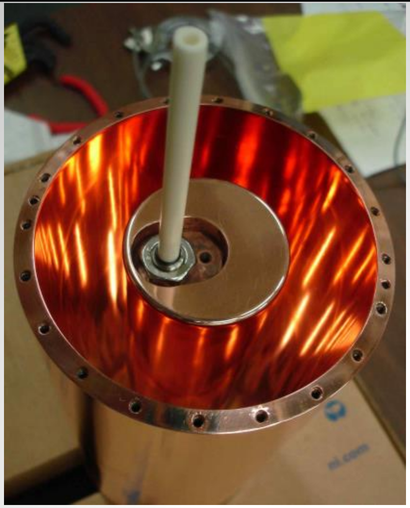
TM_{012}

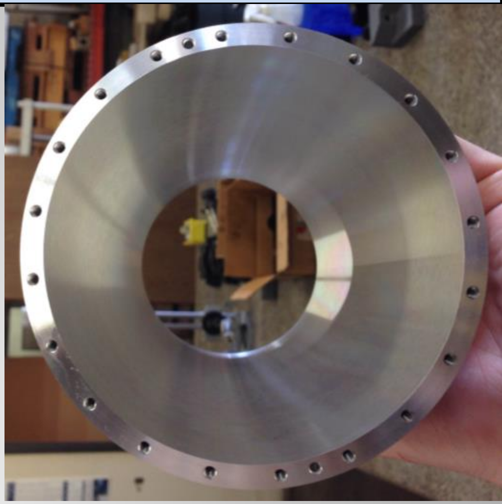


TM_{011}



School of hard knocks, high aspect ratio cavities.



- Asymptotic form-factor C achieved only for rod-endcap gap G < 100 μ
- Avoiding mode localization requires very limit of achievable machining, alignment tolerances and current hardware for cavities *L* (10 cm)~5-6GHz.
- Asymptotic form-factor C achieved only for rod-endcap gap G < 100 μ. What about 6-10 GHz cavities of similar length?
- Finer tuning motion, controlled manufacturing. Tolerances are compounding
- Ground tuning rod, diamond tooling, ground alumina tubing.

Aluminum Cavities as next generation prototype.

- Not pure 6061 is alloyed up to 1% also Mg & Si; Cr, Cu, Fe, Ti, Zn
- Room temperature a Q of 20-22k achieved with hand polishing up to 5 micron diamond lubricant.- but increases tolerance on i.d of barrel

$$Q = \frac{\mu}{\mu_c}\left(\frac{V}{S\,\delta}\right) * (\text{Geometrical Factor})$$

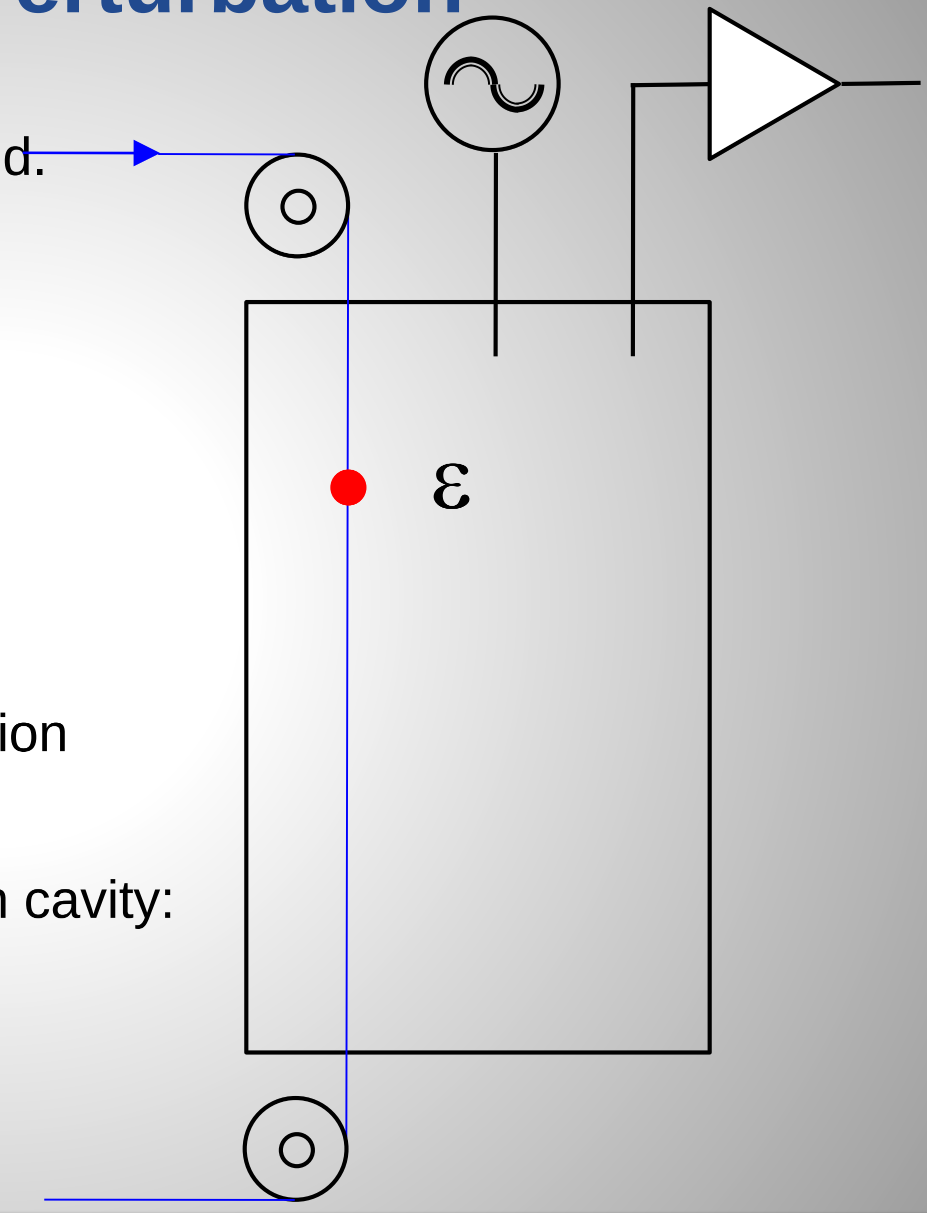
- A ratio of Q values $\frac{Q_{Al}}{Q_{Al'}} = \frac{Q_{Cu}}{Q_{Cu'}}$ is purely geometrical insightful for determining prospect of different materials.
- Predicts Q of 10k-11K with measured Cu and Cu' of 13k & 26k respectively.
- LHe dunk test yields a Q of 56k for Al barrel, from room temp to 4k expect a factor of 4 increase in Q.
- Rf-Plasma deposition chamber to construct cavities of pure materials

Bead Pull - Dielectric Perturbation

- A measurement of the resonant frequency shift measures Electric Field.
- Use of high permittivity and low loss material to perturb the field.
- Alumina ceramic with an $\varepsilon \sim O(10)$
- Physical size of bead determines the spatial resolution.
- The Volume & ε determine $\delta\omega$, precision to determine mode crossing regions.

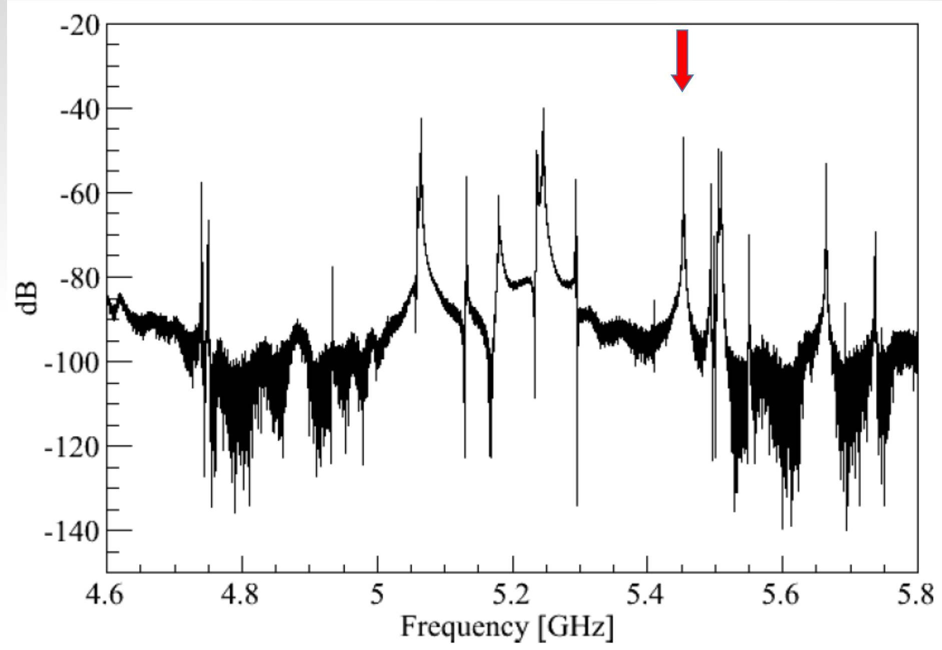
Frequency shift due to dielectric bead in cavity:

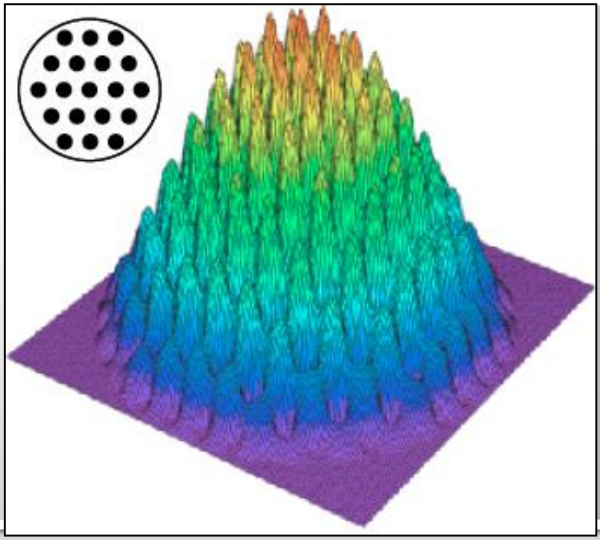
$$\frac{\delta\omega}{\omega_1} = -\frac{(\epsilon - 1)|E(r)|^2 \pi a^2 \ell}{2\langle |E|^2 \rangle_V V}$$



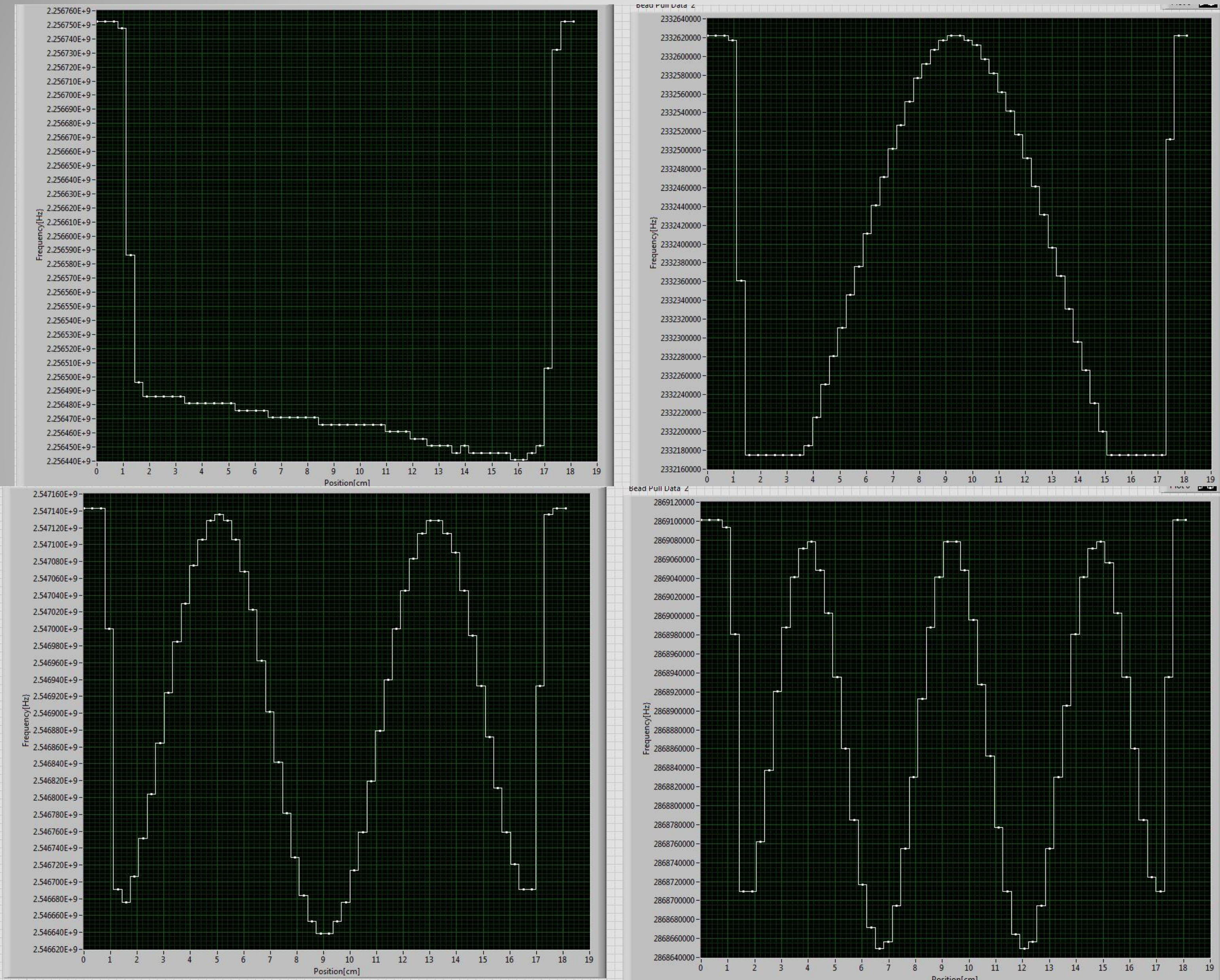
Bead-perturbation technique and relevance for ADMX-HF

- Locating the TM_{nlm} based on mode symmetry.-problem in previous experiments
- Shows mode localization from misalignments and critical coupling.
- Provides a quantitative measure of mode-mixing. What frequency space should be excluded in data taking ~(25%).
- First step in experimental validation designs of complex resonators i.e photonic band gap & high aspect ratio cavities.
- In situ use of this technique?





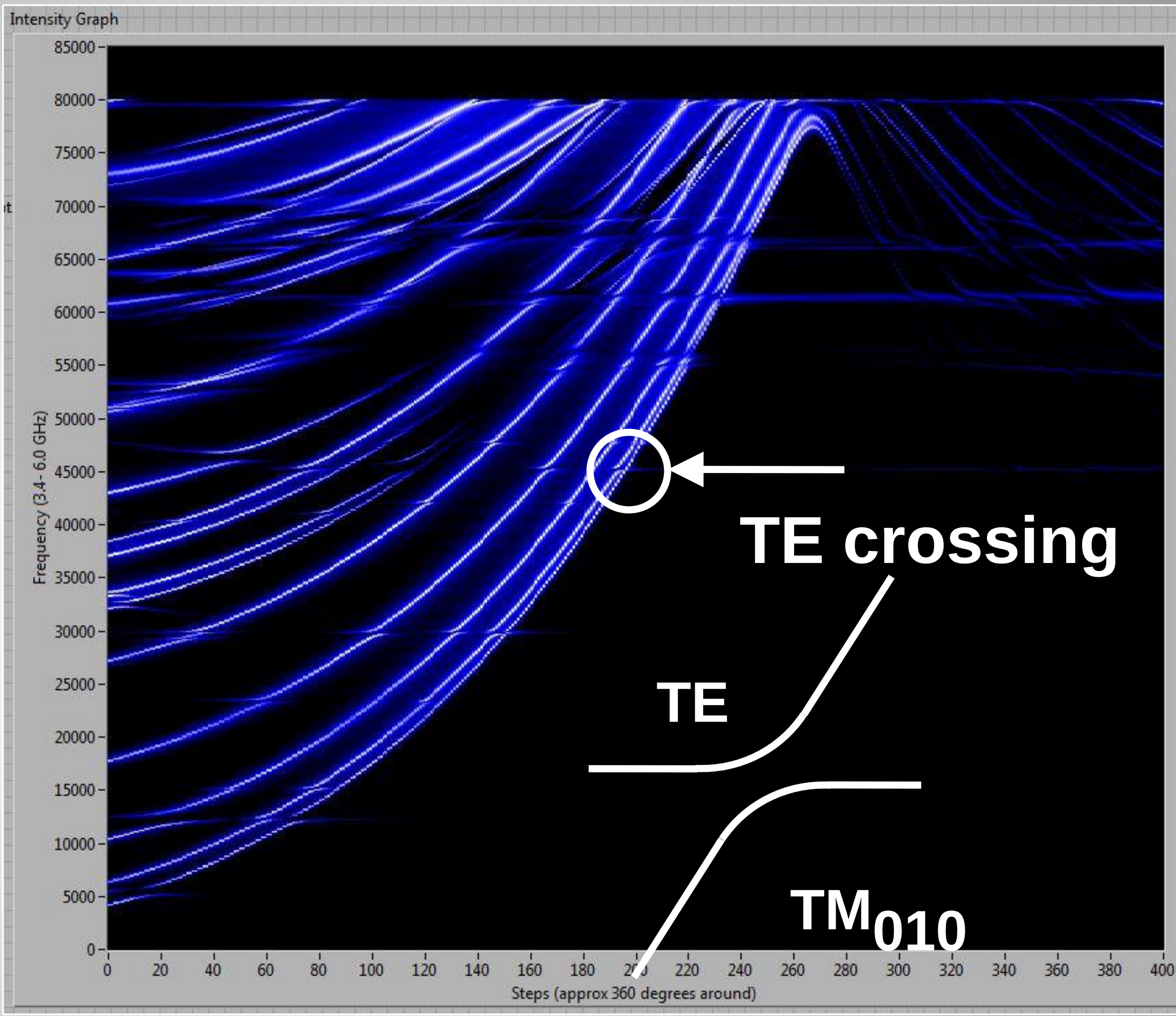
Mode determination: Empty barrel

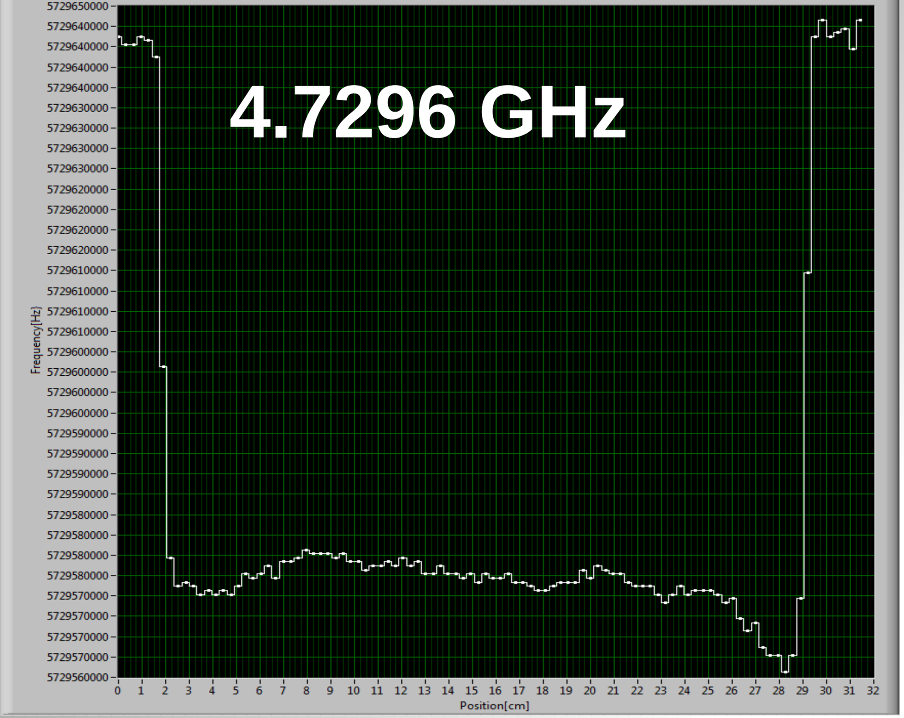


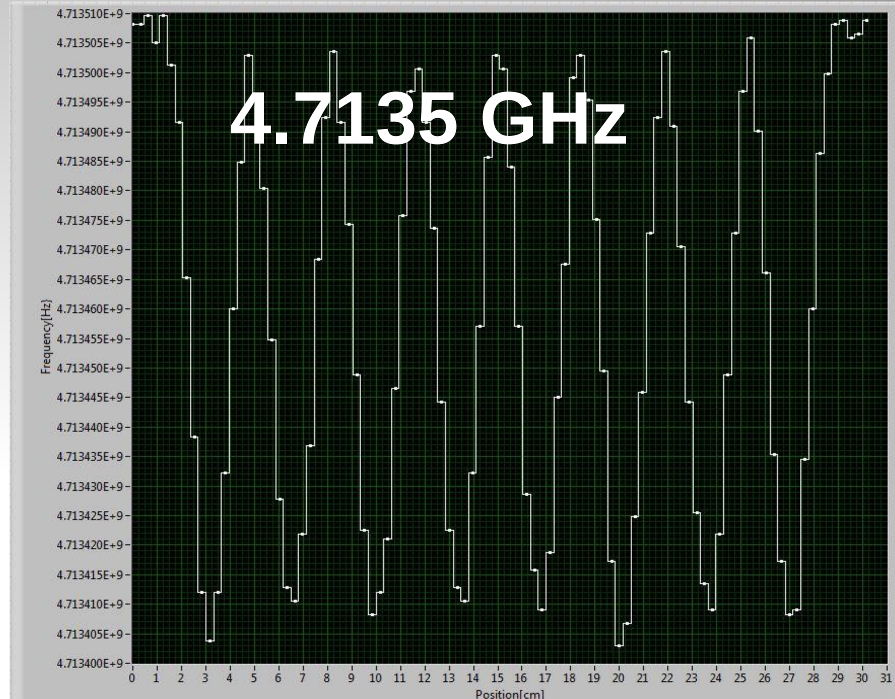
Note asymmetric behavior of TM_{010} in the first plot.

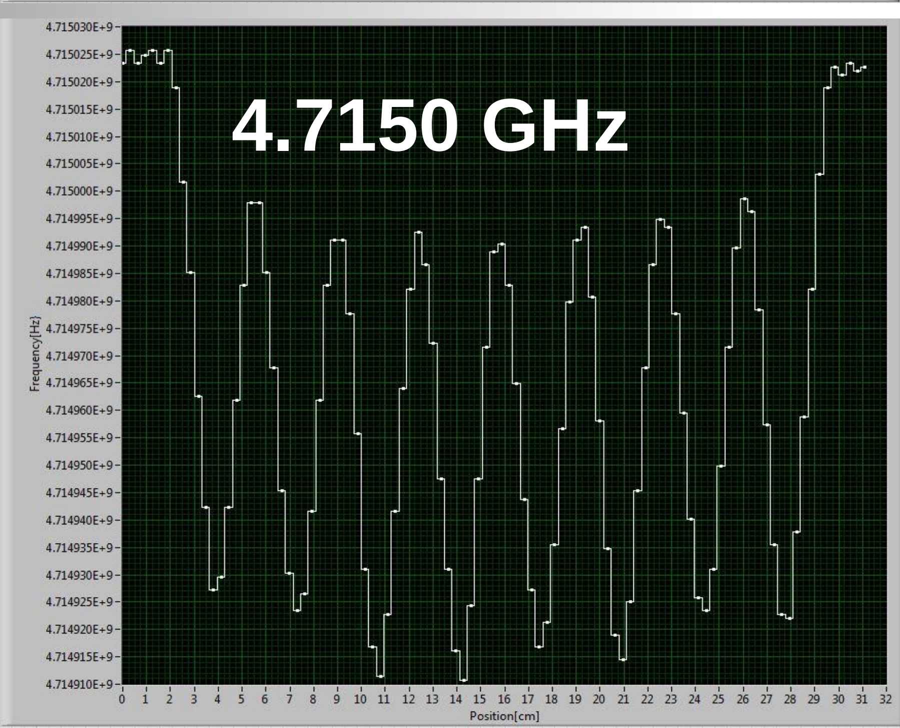
Mode crossings

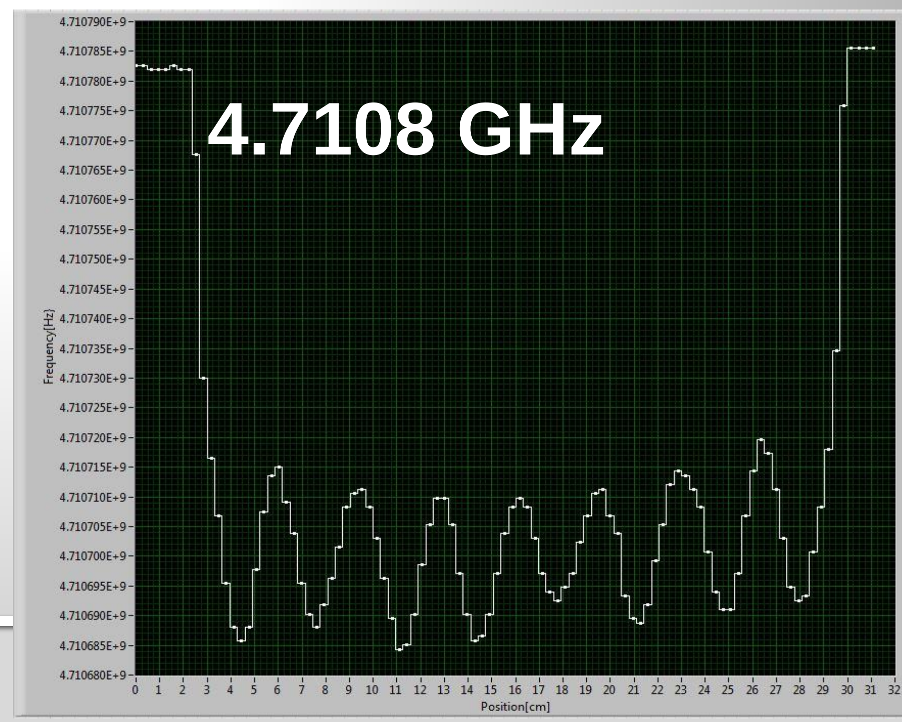
- How close to a mode crossing is still a viable data taking region?
- What indications mode mixing?
- The inability to critically couple.
- Q value rapidly decreases as mixing occurs.




4.7296 GHz
Frequency[Hz]
Position[cm]

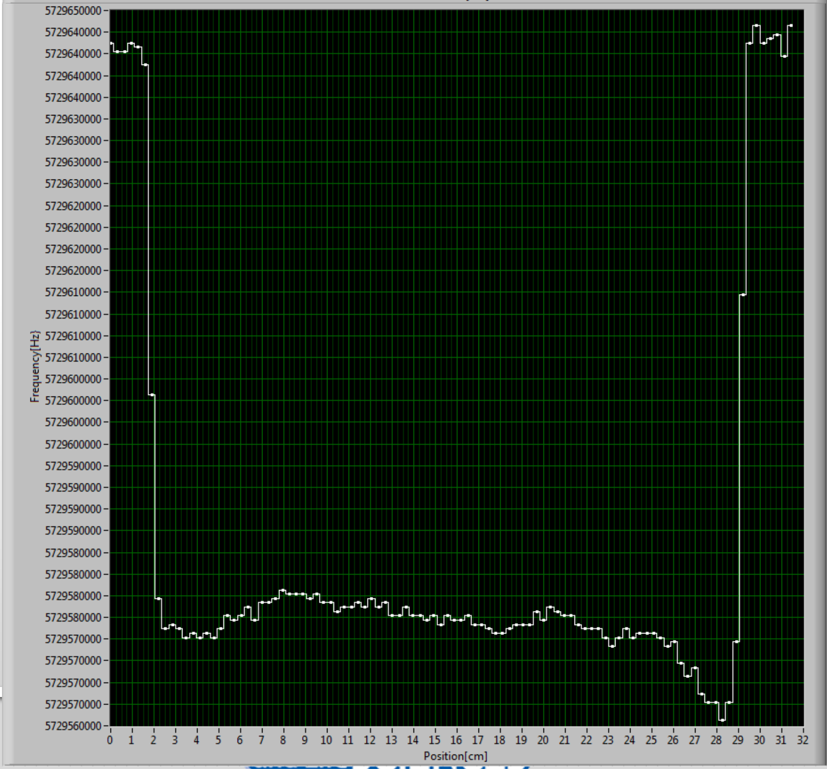

4.7135 GHz
Frequency[Hz]
Position[cm]


4.7150 GHz
Frequency[Hz]
Position[cm]

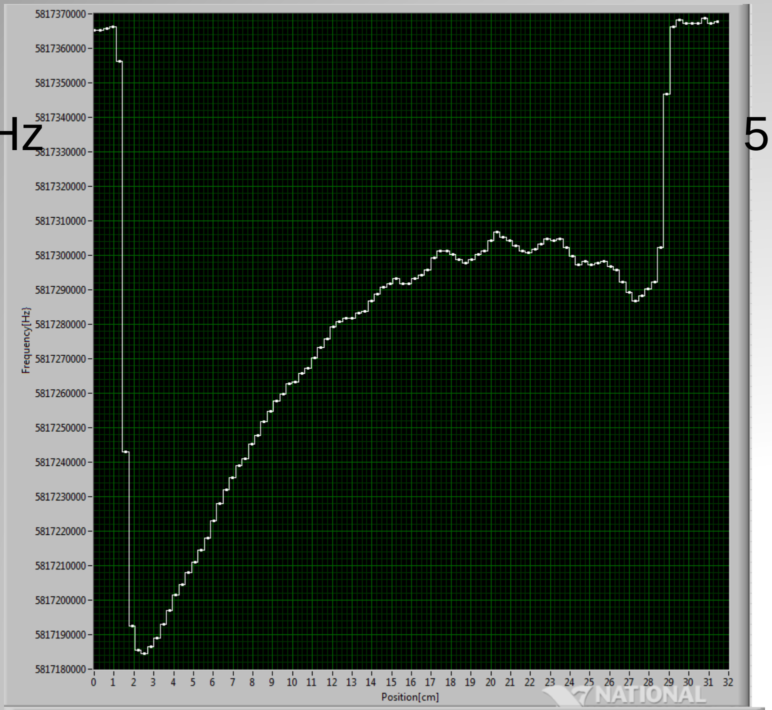

4.7108 GHz
Frequency[Hz]
Position[cm]

Mode Localization:

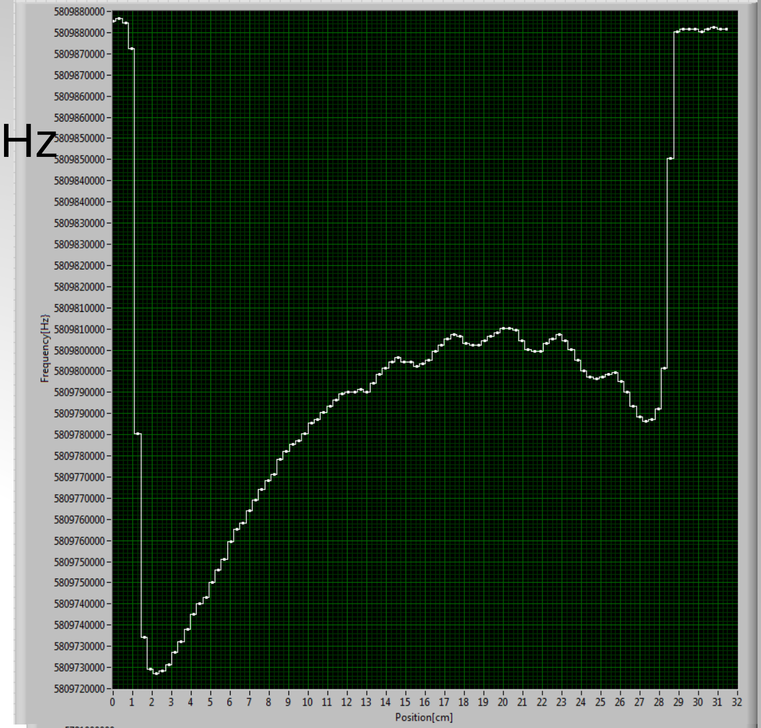
- Geometrical configuration defines boundary conditions which governs the electric field.
- Misalignments lead to mode localization where the Electric field structure is deformed and high form factor lost.
- Failed geometry also leads to additional modes.-more lost data.
- Offsets of the tuning rod on the order of mils (0.001”) are significant.
- Compare the distance of the rod to the wall of cavity and the offset of tuning rod. ex 1” radial gap and 0.010” offset.



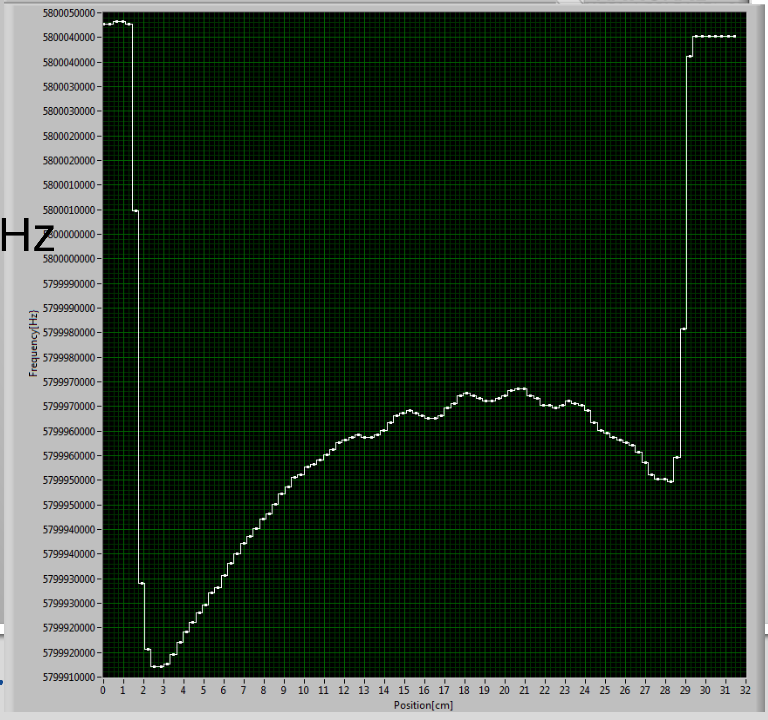
5.817GHz



5.809GHz



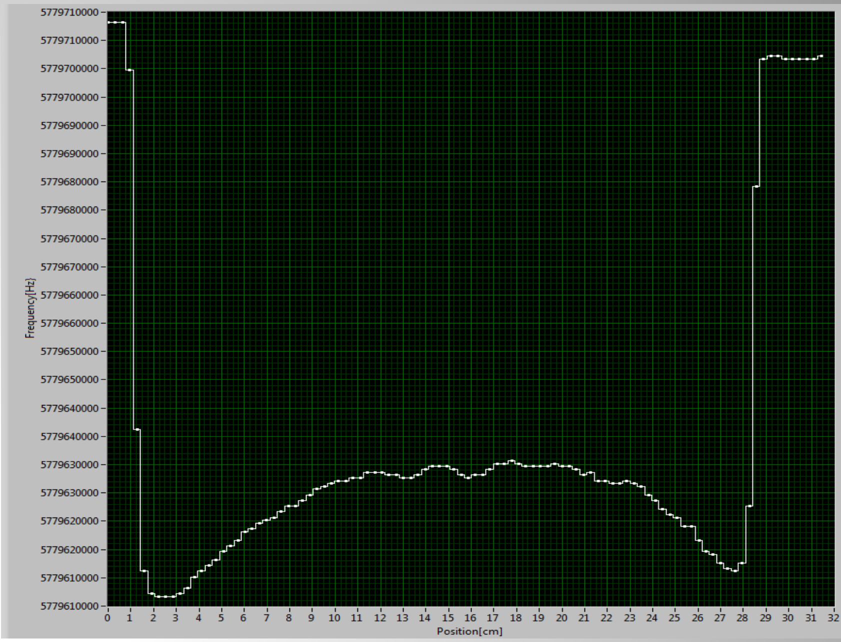
5.800GHz



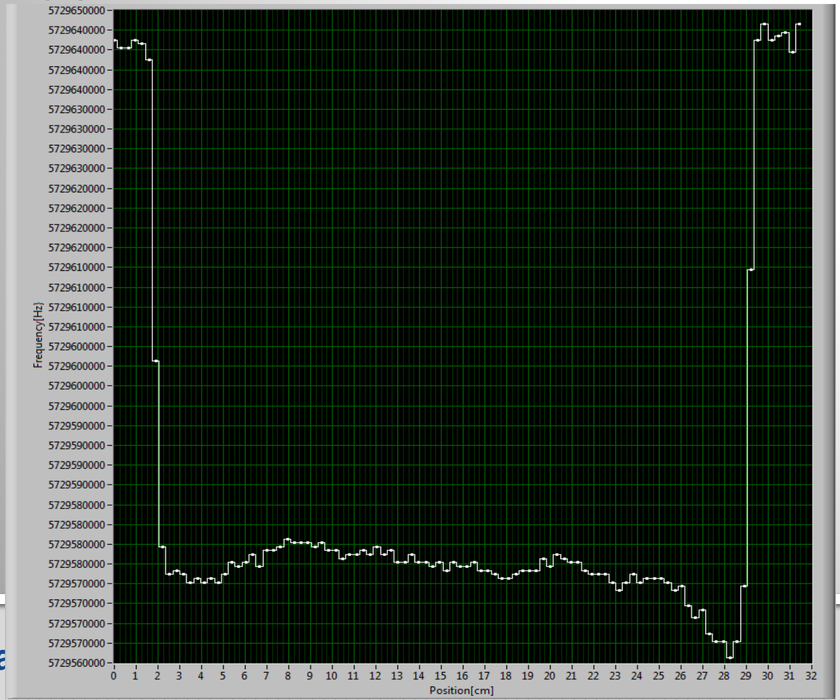
5.791GHz

5.791GHz

5.779GHz

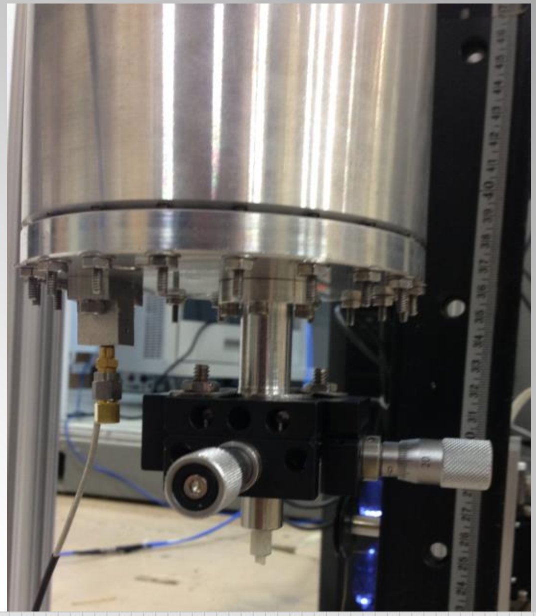


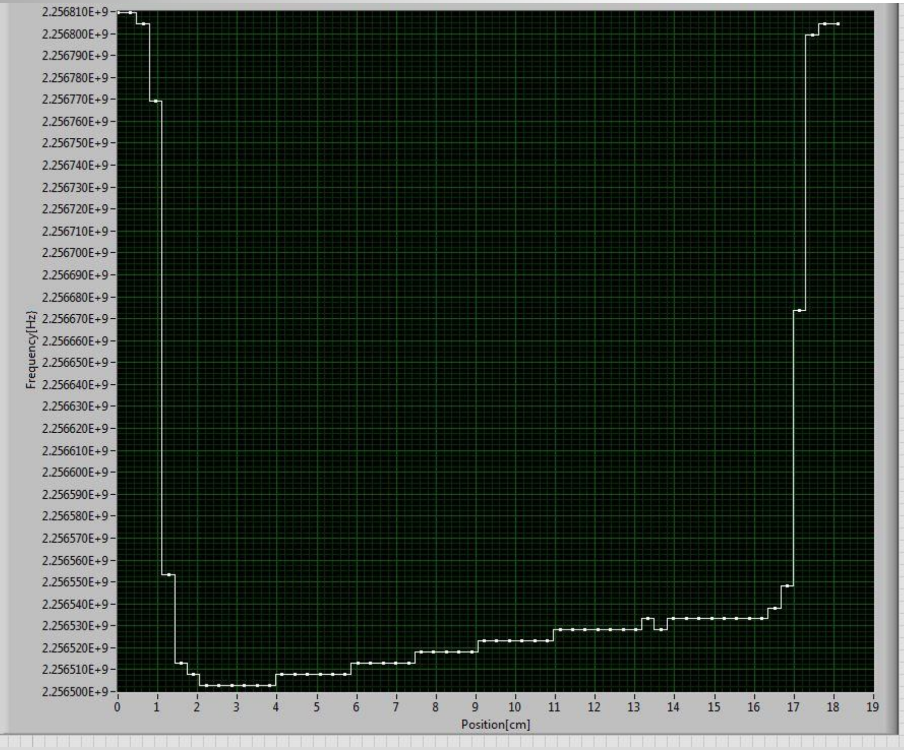
5.729GHz

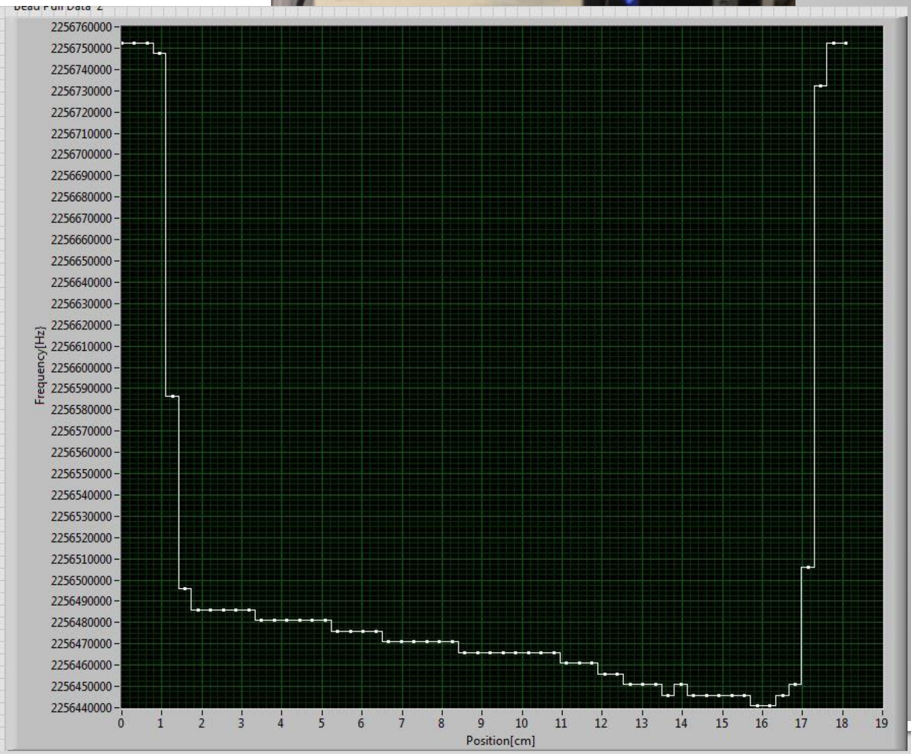


Mode localization

- Mode localization induced from antenna coupling.
- Now performing sensitivity studies of mode localizations due to induced misalignments of the tuning rod.

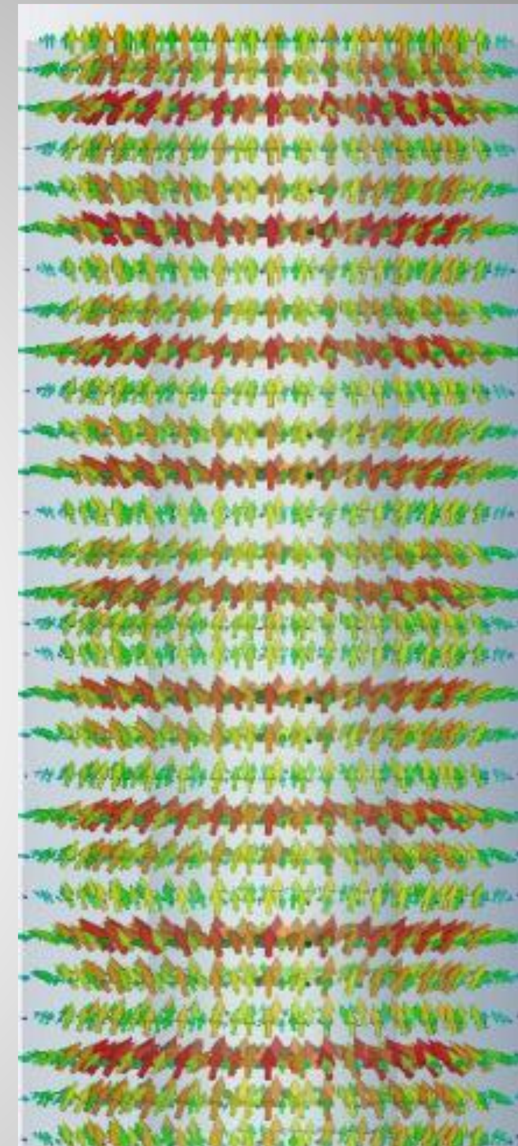






Mode Crossings

- Mixing of the leads to degradation of the form factor & limits available frequency space.
- Use of different aspect ratio cavities enable the mixed modes to shift allowing for continuous frequency space.
- Currently testing of copper knife edge inserts & larger tuning rods to boost frequency.



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